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BRITTLE FAILURE MECHANISMS OF ROCK

FINAL REPORT

W.F. Brace

April 1979

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The findings of this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

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Brittle fracture, faulting, crack growth, thermal stress, thermal expansion, thermal cracking

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

At high compressive stress, microcracks in rock lengthen in the stress direction. Slender columns of unbroken material are left between the cracks; SEM measurements of length/width ratio of these columns suggest that some could have buckled under the loads applied in the experiments, and thus been the source of the sudden instability at faulting.

Thermal expansion of rocks was measured under high pressure for the first time; below some critical pressure, thermal cracking

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occurred, due both to thermal gradients and anisotropy in thermal expansion of the minerals. Observed thermal expansion at high pressure was close to Walsh's theoretical bounds; thus, thermal expansion of rocks under pressure can be calculated with sufficient accuracy for many applications.

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STATEMENT OF PROBLEMS STUDIED

In spite of extensive research during the past ten years [1], the brittle failure of rock is still poorly understood. For example, one cannot predict even approximately the absolute stress at which faults or tension fractures form. Brittle failure and fault formation both in rocks and brittle solids in general [2, 3, 4] are thought to be related to dilatant microcracks, but the relation of such cracks to a fault remains obscure. Attempts [5, 6, 7] have been made to improve our understanding of crack growth, but progress has been extremely limited. The optical methods used suffer in that many microcracks cannot be resolved, and so the transition from microcracks to a fault cannot be traced. Peng and Johnson [6] proposed a theory of fault formation based on the stability of columns of rock between microcracks, but this cannot be tested until geometric details of the columns become available.

Our recent studies of microcavities in rocks using the scanning electron microscope [8, 9, 10] have shown that any features hitherto invisible are now available for quantitative examination. We applied our new technique to the development of dilatant microcracks [11] and to permeability of granite [12]. In the present study, we have used the SEM along with our high pressure, high temperature deformation apparatus to study several aspects of brittle deformation of rock:

(1) a test of the column collapse model of Peng and Johnson [6]; (2) crack growth under thermal stress; and (3) the relationship of fault growth to cracks and grain boundaries.

SUMMARY OF RESULTS

Virtually all of our work has appeared, or will appear, in published articles. Two abstracts are appended below, covering work which is in press, and some of the highlights of this and our ongoing work are given here.

1. Faulting in brittle rocks is a very unstable process, and the source of the instability is as yet unknown. Since the instability occurs at peak stress, a correct description of the instability may provide a way of calculating peak stress. Peng and Johnson [6] proposed that the instability was due to the buckling of tiny columns which formed between growing dilatant microcracks. In Figure 1 such a situation is shown for a sample of Westerly granite close to peak stress. The en échelon cracks are evident, as well as the slender columns of rock which remain intact between them.

According to the Peng and Johnson model, elastic buckling of these columns triggers the faulting instability. Our approach was to determine dimensions of such columns from SEM photographs such as Figure 1. Using the theory of elastic buckling, we then determined whether such columns were elastically unstable under the loads applied during the experiment. The results reported in the appended paper by Schwenn and Brace suggest that buckling could indeed have begun. Some measurements from that paper are summarized in Figure 2, showing a frequency distribution of column length to width. The critical ratio for buckling was 12. It is seen that some of the observed columns exceed this ratio, and therefore would have been unstable. In terms of stress-strain behavior this rock sample was at or just beyond peak stress, where one might have expected that collapse of the sample was imminent; imminent collapse is suggested by the measurements in Figure 2.

Unfortunately, the above result is not very clearcut. For one thing, it would be difficult to use data such as that shown in Figure 2 to predict an accurate failure stress. Also, the critical ratio for buckling depends on details of column geometry which are not obvious. Thus, for example, the way a column is attached at its ends has a strong influence; unfortunately this cannot always be judged from photographs. However, our results are suggestive, and we intend to pursue further tests of this model.

2. The thermal expansion of rocks when measured at or near room pressure is often unpredictable and irreproducible, due in part to thermal cracking. We developed an experimental method for the measurement of thermal expansion under confining pressure (Appendix) and found that 50-250 bars pressure suppressed thermal cracking. We analyzed the source of the cracking and found that it could be traced to two effects, the thermal gradient, and the difference in mineral thermal expansions. The principal application to brittle failure in rock is that thermal cracking assists the normal crack growth. Thus studies of brittle failure alone have to be done at pressures above the critical pressure to suppress thermal cracking.

Although the role of thermal cracking in brittle fracture was of primary interest to the project, there was one significant by-product of our work. We were able for the first time to observe the true thermo-elastic behavior of rocks and, thus, to measure intrinsic thermal expansion. The technique, described in the appended paper by Wong and Brace, was a simple, although novel, procedure which should find wide application. Thermal expansion is a poorly understood characteristic of rocks but one which is very important for many geothermal applications and for some geotechnical aspects of radioactive waste disposal.

3. We observed brittle fracture in a series of high temperature, high pressure deformation experiments. In 17 experiments at 4 kbars, temperatures ranged from 200 to 600°C, at three different strain rates. Typical examples are shown in Figures 3 and 4. In the three curves in Figure 3 it is seen that the steepness beyond peak stress becomes less at higher temperature. This enabled partially fractured material to be obtained for SEM study. We are looking particularly at material in the range 200 to 400°C, as it is evident from other work [13] that plastic processes do not yet play an important role. Detailed results will be reported in a forthcoming PhD thesis of T.F. Wong.

PERSONNEL

The following were involved in the research supported by this contract:

Mary B. Schwenn	Received MS degree, 1977
Teng-fong Wong	Will receive PhD degree

In addition, W.F. Brace (Principal Investigator), D.A. Hirst (Project Machinist), and M. Slavin (Administrative Assistant) played significant roles in the program.

W F Brace

W.F. Brace
Principal Investigator

April 1979

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APPENDIX - Abstracts

Buckling as the faulting instability for Westerly granite

by M.B. Schwenn and W.F. Brace

Abstract

Peng and Johnson [1972] proposed that the area between axial cracks in Chelmsford granite behaves like a slender column. They suggest that the buckling of these columns accounts for the instability observed during faulting.

The mechanism proposed by Peng and Johnson for the formation of a fault is investigated for Westerly granite. En échelon crack arrays were located in the quartz grains of the sample, using the SEM. The dimensions of the regions between these crack arrays were measured and the apparent slenderness ratios - length/width of column - were computed for each of the observed columns. Some of these slenderness ratios exceeded that ratio which would have buckled. Hence buckling of some of the observed columns could have occurred.

Thermal expansion of rocks:
Some measurements at high pressure

by T.-F. Wong and W.F. Brace

Abstract

The thermal expansion of rocks has customarily been measured at room pressure; it is typically irreversible after heating above room temperature and the coefficient of thermal expansion of a rock is usually much larger than the average coefficients for the minerals in the rock. We measured coefficients of thermal expansion of rocks under sufficient pressure that the strains were reversible; the coefficients obtained fell close to the theoretical bounds for polycrystalline aggregates calculated by Walsh. Thus, within the limit of assumption in the theory, Walsh's theoretical bounds gave a good estimate of the intrinsic thermal expansion of rocks.

The thermal expansions were measured by strain gauges attached to copper-jacketed samples of granite, diabase, marble, limestone, dunite and quartzite. The temperature range was 2° to 38° and confining pressure ranged up to 600 MPa. Confining pressure had a small effect as long as pressure was greater than some critical value which apparently was the minimum needed to prevent thermal cracking and other non-elastic

effects. The critical pressure depended on rock type and on thermal history of a sample. We propose theoretical models to explain the effects of temperature on the opening of cracks at high confining pressure, and the propagation of open cracks at low pressure induced by thermal gradient or internal stresses.

Fig. 1

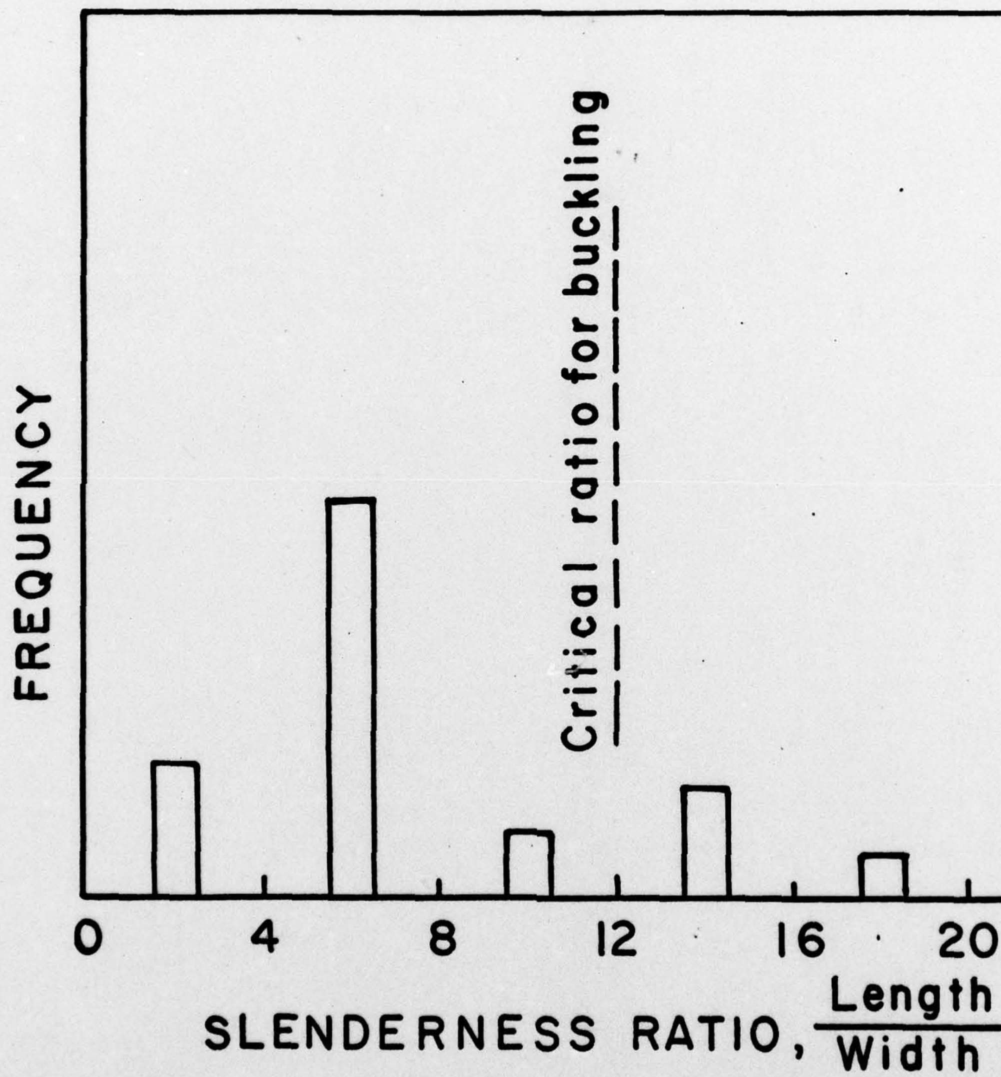

Fig. 2. Frequency distribution of slenderness ratio of columns between microcracks. The dashed line gives that ratio that would buckle under the applied load of the experiment.

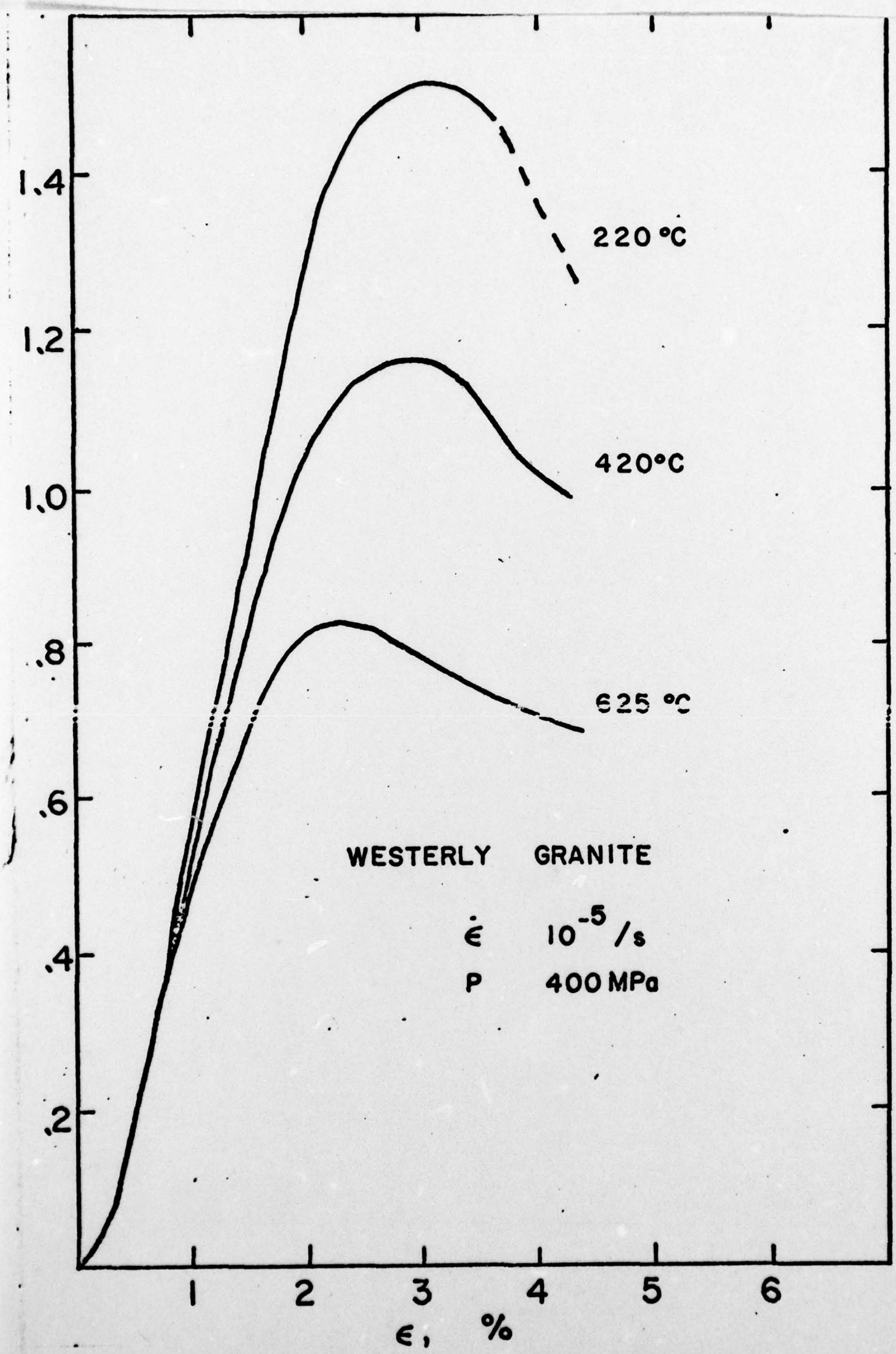

Fig. 3. Stress-strain behavior of Westerly granite as a function of temperature. Note the gradual flattening of the post-peak region.

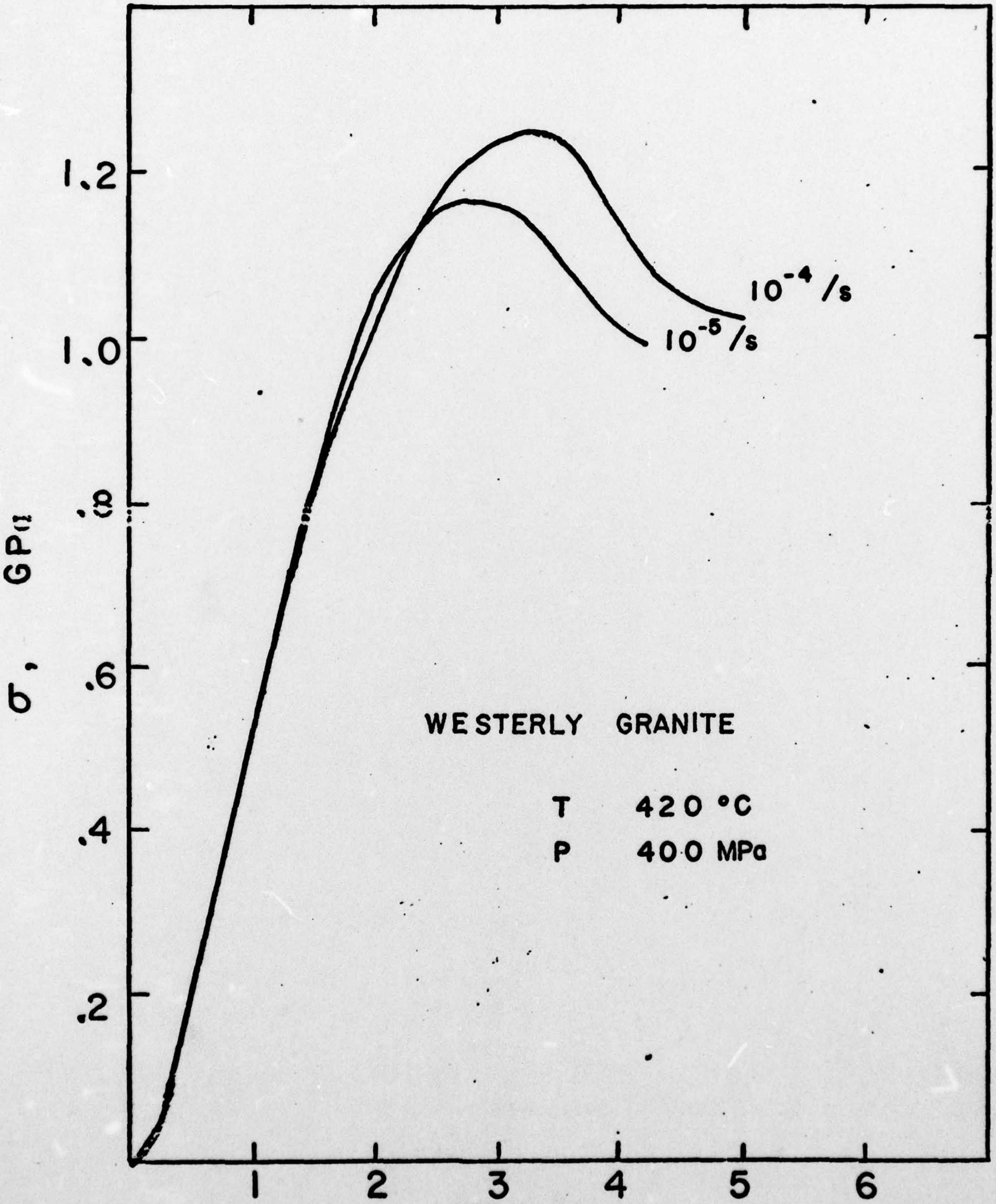

Fig. 4. Stress-strain behavior of Westerly granite as a function of strain rate.